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(54) **Surface wave devices**

(57) A surface wave device comprising a laminate formed of semiconductor layer S, intermediate protective layer I' and piezoelectric layer I has an electrode M_1 on layer I for supply of a d.c. bias voltage and an a.c. electrical signal, and a second electrode M_2 on layer S. As shown a transducing arrangement produces surface waver B, B', the latter being absorbed at A. In a second embodiment, surface waves travelling between interdigital transducers on layer I are parametrically amplified by pumping signals applied to electrode M_1.

FIG.1

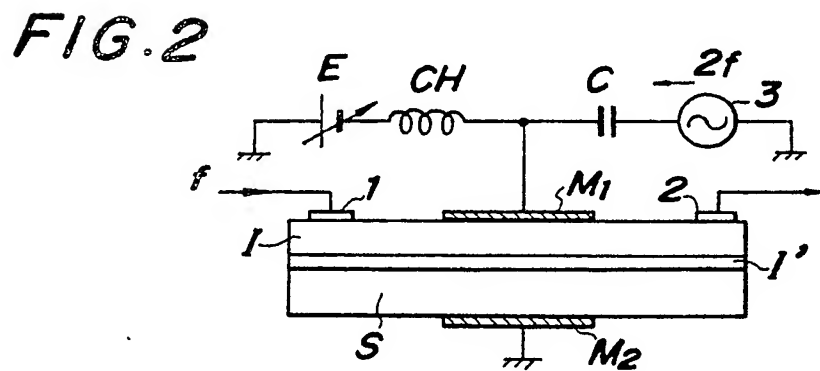GB 2 004 157 A

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FIG.1

E   1 sheet   CH   C   F

A   M₁   I

B'   B

I'   I'

M₂   S

FIG.2

E   CH   C   2f   3

f   1   M₁   2
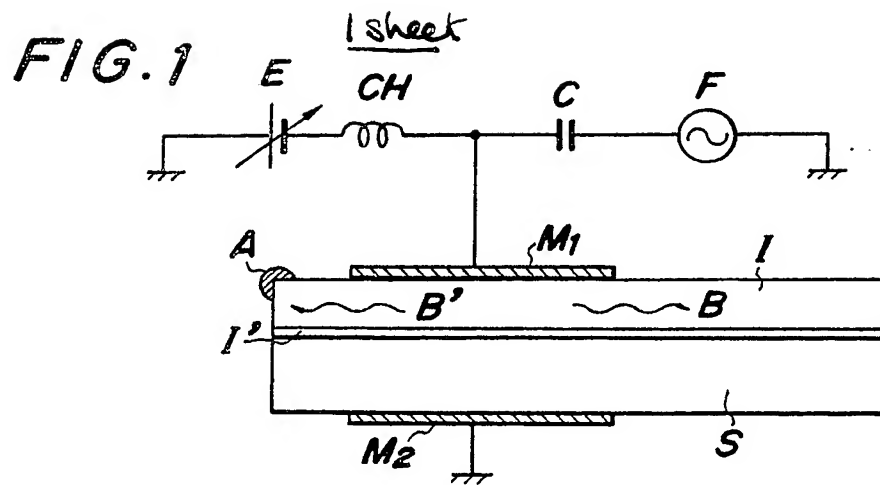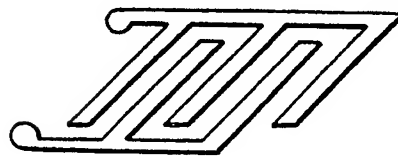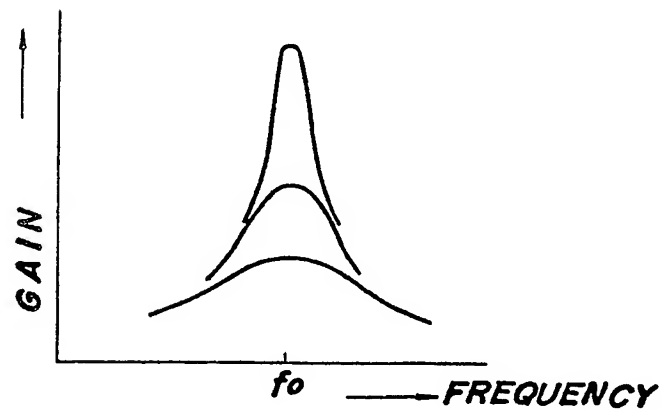
I   I'

S   M₂

FIG.3

FIG.4

GAIN

fo   FREQUENCY
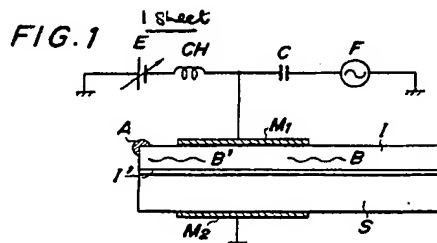
SPECIFICATION

Surface wave device

5 This invention relates to an elastic surface wave
device, and more particularly to an elastic surface
wave device operative by a parametric amplifying
effect.
   An elastic surface wave amplifier is a solid-state
10 amplifier which generally employs a piezoelectric
semiconductor or a suitable combination of a semi-
conductor and a piezoelectric material, and attains a
desired amplification effect by interaction between
an elastic surface wave (hereinafter referred to as
15 'surface wave') and a semiconductor charge.
   In a conventional elastic surface wave amplifier, a
piezoelectric material such as lithium niobate and a
semiconductor are disposed oppositely so as to be
spaced a distance of about 1,000 Å and a d.c. voltage
20 is applied to the semiconductor in a direction along
the surface of the semiconductor which defines the
gap to accomplish an amplifying operation by the
interaction between a semiconductor charge and a
surface wave caused by such application of the d.c.
25 voltage.
   This conventional amplifier, however, has a defect
that continuous wave cannot be obtained due to
Joule heat generated by the d.c. current. It has
another difficulty in integration because of its non-
30 monolithic structure.
   There have been other conventional devices than
that of d.c. voltage-application type, which utilize a
parametric amplification effect. One of them is so
constructed that a semiconductor material such as Si
35 is provided in the propagation path of travelling
wave on a piezoelectric material through a conduc-
tive liquid and so operated that a surface signal wave
and a pumping wave (travelling wave) are travelled
in the same direction at a portion of the piezoelectric
40 material and a space capacitance nonlinearity at a
portion of the semi conductor is utilized to attain
amplification of the surface signal wave.
   This device, however, has such disadvantages that
since the frequency of the pumping wave is much
45 higher than that of the surface signal wave, there is
some difficulty in the preparation of transducers for
generating the pumping waves, and that since
necessary pumping power is increased due to gen-
eration of harmonic components of the pumping
50 wave, there is caused some disadvantage in actual
operation. It has further disadvantage in integration
too.
   Another type of conventional parametric amplifier
is so operated that with respect to surface wave
55 signal propagating on a piezoelectric material, an
exciting voltage is applied to a metal electrode pro-
vided in the propagation path for exciting the
piezoelectric material at the relevant portion, thereby
to amplify the surface signal wave propagating
60 through the piezoelectric material due to nonlinear
effect of the piezoelectric material.
   According to the present invention, there is pro-
vided an electric surface wave device, comprising a
laminate composed of a semiconductor layer, a
65 piezoelectric material layer, and a protective film

layer interposed therebetween; a first electrode on a
surface of said piezoelectric material layer for appli-
cation of a.d.c bias voltage and supply of a pumping
power; and a second electrode on a surface of said
70 semiconductor layer for ohmic contact therewith.
   It should be explained that the present invention
has been achieved based on the finding that when a
surface charge layer capacitance nonlinearity is
imparted to a surface portion of the semiconductor
75 under the electrode and an a.c. electrical signal hav-
ing a frequency f is applied to said electrode, a sur-
face wave having a frequency f/2 is produced due to
parametric interaction and that the thus produced
surface wave is propagated in the left and right direc-
80 tion of the electrode.
   Preferred embodiments of the invention will now
be described by way of example with reference to
the accompanying drawings in which:—
   Figure 1 is an electrical circuit diagram, showing a
85 preferred form of an elastic surface wave device in
accordance with the present invention;
   Figure 2 is an electrical circuit diagram, showing
an elastic surface wave amplifier in accordance with
the present invention;
90   *Figure 3* shows one form of a comb electrodes
employable in the amplifier shown in Figure 2, and
   Figure 4 is a diagram showing gain characteristics
of the amplifier shown in Figure 2, choosing Q as a
parameter.
95   In Figure 1, character S designates a semiconduc-
tor substrate made of, for example, silicon (Si) etc., I
a piezoelectric film made of zinc oxide (ZnO) etc. and
I' a protective film such as a silicon oxide (SiO) film.
The protective film I' acts as a stabilizing film for the
100 surface of the semiconductor substrate S.
   The semiconductor substrate S, the protective film
I' and the piezoelectric film I comprise a laminate..
   The laminate may alternatively have such con-
struction that a piezoelectric material is used as a
105 substrate and a semiconductor film is formed in a
suitable manner on the piezoelectric substrate.
   The semiconductor substrate S may be either of
p-type or of n-type. In accordance with the type em-
ployed, a polarity of a d.c. bias voltage as mentioned
110 later may be determined so as to produce a space
charge layer at the surface portion of the semicon-
ductor substrate S.
   M_1 on the piezoelectric film I is a metal electrode
for supply of a d.c. bias voltage and an a.c. electrical
115 signal. The metal electrode M_1 is formed in a thin
film for example by evaporation.
   M_2 is an electrode for an ohmic contact with the
semiconductor substrate S.
   The electrode M_1 is connected to a ground through
120 a choke coil CH for choking an a.c. current and a
voltage variable-d.c. power source E for a d.c. bias
voltage application.
   This electrode M_1 is further grounded through a
capacitor C for preventing a d.c. current and an a.c.
125 electrical signal source F.
   Character A designates a sound wave (surface
wave) absorber for example made of silicon grease.
This sound wave absorber A acts to absorb one of
surface waves B, B' which propagate in the opposite
130 directions, i.e. surface wave B' in the embodiment of

Figure 1, so as to operate the device as a unidirectional surface elastic wave transducer.

The so constructed surface elastic wave device in accordance with the present embodiment will oper-
5 ate as follows:—

Explanation will be given referring to the case where an a.c. electrical signal is converted to a surface signal wave.

A suitable value of d.c. bias voltage is first applied
10 from the voltage variable-d.c. power source E to the electrode M_1 to impart the semiconductor substrate S at its surface portion with a surface charge layer capacitance nonlinearity.

When an a.c. electrical signal having a frequency f
15 is then supplied from the a.c. electrical signal source F to the electrode M_1, surface signal waves B, B' of a frequency f/2 is generated by the parametric interaction between the power of the very a.c. electrical signal and the surface charge layer capacitance non-
20 linear characteristic. These surface signal waves B, B' are propagated in directions right and left of the electrode M_1 as viewed in Figure 1.

At this time, if the frequency of the a.c. electrical signal to be supplied to the electrode M_1 is selected
25 so as to be 2f, the frequency of the surface signal waves B, B' converted is f. Thus, when the frequency of the a.c. electrical signal is varied over a wide range, the surface signal waves B, B' having the corresponding frequency are generated.

30 The amplitude of the converted surface signal waves B, B' varies depending upon the length of the electrode M_1 in the propagation direction of the surface signal waves and the gain of the nonlinearity at the surface portion of the substrate.

35 The gain of the nonlinearity is determined by the surface charge layer capacitance nonlinearity which is in turn determined by a d.c. bias voltage value and the amount of the a.c. electrical signal power to be supplied.

40 Accordingly, in practical implementation, the frequency and power of the a.c. electrical signal and the gain of the nonlinearity may be suitably selected to produce a surface signal wave of the corresponding frequency and the amplitude.

45 Furthermore, when a sound wave absorber A is mounted on one end of the piezoelectric material as shown in Figure 1, the surface signal wave B' propagating in the direction towards the absorber is absorbed and not reflected, so that there is provided
50 an unidirectional elastic surface wave transducer.

The foregoing description is given referring only to the conversion from an a.c. electrical signal to a surface signal wave, the conversion in the opposite direction, i.e. from a surface signal wave to an a.c.
55 electrical signal is accomplished in substantially the same manner.

Though the piezoelectric material I is made of zinc oxide in the illustrated embodiment, it may alternatively be made of other piezoelectric materials such
60 as lithium niobate ($LiNbO_3$), aluminum nitrate (A1N), cadmium sulfide (CdS), zinc sulfide (ZnS) etc.

In the light of the foregoing description, it is easily understood that in accordance with the present invention, a semiconductor and a piezoelectric ma-

substrate and a film provided thereon, respectively, for providing a monolithic formation so that it can improve the reproducibility and attain the integration.

70 The above arrangement has a further advantage that since the configuration of the electrode mounted on the surface of the piezoelectric material may be freely designed and it may be of a plain sheet, there is no need to subject the material to
75 elaborate processing so long as it can produce a necessary space charge layer.

As the disclosed device accomplishes the conversion between an a.c. electrical signal and a surface signal wave utilizing a parametric effect, the fre-
80 quency range can be widened so that the conversion can be effected even in a ultra high frequency band, with an excellent efficiency, where conventional techniques cannot achieve the conversion.

Figure 2 shows another embodiment of the pre-
85 sent invention, wherein the elastic surface wave device is applied for an amplifier. In the figure, like members are designated by like numerals or characters.

Numerals 1 and 2 designate input and output
90 means, respectively, for electrical signals, and they include comb electrodes as shown in Figure 3. At the input means 1, an electrical signal is converted to an elastic surface wave, and at the output means 2 the surface signal wave is converted to an electrical
95 signal.

An electrode M_1 is connected to a ground through a capacitor C for preventing a d.c. current and a high-frequency power source 3 for supply of a pumping power.

100 The so constructed elastic surface wave amplifier in accordance with the present invention will operate as follows:

Upon supply of an electrical signal to the input means 1, the electrical signal is converted to a sur-
105 face signal wave, which is then propagated at the surface portion of a piezoelectric material I towards the output means 2. The frequency of the surface signal wave being propagated is now assumed to be f. Then, when a pumping power having a frequency
110 2f is supplied to the electrode M_1 on the piezoelectric material I from a high-frequency power source 3 as well as a d.c. bias voltage from a d.c. power source E, the surface signal wave is amplified by a parametric interaction due to the surface charge layer capaci-
115 tance nonlinearity at the surface portion of a semiconductor S under the electrode M_1. The so amplified surface signal wave is converted to an electrical signal by the output means 2 and drawn out.

120 The gain in the above-mentioned amplifying operation is expressed as a function of the length of the electrode M_1 in the propagation direction of the surface wave, the gain E of the nonlinearity at the surface portion of the semiconductor substrate, the fre-
125 quency of the pumping power etc. Accordingly, the gain can be varied by varying the values of the respective parameters.

The gain E of the nonlinearity is determined by a surface charge layer capacitance nonlinearity of the

value of a d.c. bias voltage applied and the amount
of the pumping power. Accordingly, in a practical
application, these two parameters may be advan-
tageously varied to regulate the gain.
5   Thus, in the elastic surface wave amplifier in
accordance with the present invention, the
amplification depends highly on the surface charge
layer capacitance nonlinearity at the semiconductor
substrate S of silicon etc. The effect due to this non-
10 linearity is by far excellent as compared with that of
the conventional technique which utilizes non-
linearity of the piezoelectric material itself, which
results in various advantages such that the required
pumping power can be much reduced to obtain a
15 given gain.
    As the parametric amplifying effect of the elastic
surface wave amplifier in accordance with the pre-
sent invention is a kind of a positive feedback amp-
lifying effect, an electrical quality factor Q is required
20 to be improved to enhance the gain. One example of
the frequency response of the gain with varying Q
values is shown in Figure 4. As apparent from the
figure, a frequency band width can be varied as well
as the gain. Thus, the amplifier of the present inven-
25 tion further has a variable band width-amplifying
effect.
    For supply of the pumping power having a fre-
quency of 2f, one high-frequency power source 3 is
employed in the embodiment shown in Figure 2, but
30 two or more high-frequency power sources may be
employed so long as the beat frequency thereof is
equal to 2f. For example, when high-frequency
power sources having frequencies of f_1 and f_2,
respectively, are employed, a power having fre-
35 quency components of $f_1 \pm f_2$ and $nf_1 \pm mf_2$ is pro-
duced due to the nonlinearity at the surface portion
of the semiconductor substrate.
    If the frequency of the so obtained power is equal
to 2f, it can accomplish the amplification of the sur-
40 face signal wave as when one high-frequency power
source is employed.
    Though the foregoing description is given refer-
ring only to the pumping power having a frequency
2f, the frequency of the pumping power is not limited
45 to 2f and it may be 4f, 6f, 8f ...
    In effect, however, the frequency of the pumping
power is preferred to be 2f because the pumping
power having a frequency 2f provides the maximum
gain E of the nonlinearity. In this connection, it is to
50 be noted that when the frequency of the pumping
power is changed, the center frequency of the fre-
quency band capable of being amplified is variable.
In brief, the elastic surface wave amplifier in accor-
dance with the present invention has a variable band
55 width-amplifying function. Accordingly, it can work
also as a band pass filter variable in frequency band
width and center frequency.
    Though, in the embodiment as shown in Figure 2,
the electrode M_1 is provided intermediate the input
60 means 1 and the output means 2 and only the sur-
face signal wave which is transmitted through the
electrode M_1 and amplified is drawn out of the out-
put means 2, the elastic surface wave amplifier in
accordance with the present invention can essen-
65 tially produce a reflected signal wave at a portion of

the electrode M_1 as well as the transmitted signal
wave and utilize the reflected wave signal for
amplification effect as the transmitted signal wave.
Accordingly, if the output is disposed intermediate
70 the input means 1 and the electrode M_1, an electrical
output can be drawn out by the reflected signal
wave. In this case, however, it is required to employ
a uni-directional elastic surface wave transducer as
the output means.
75 The semiconductor to be employed may be either
of p-type and n-type. The polarity of the d.c. power
source for the bias voltage is chosen depending on
the type selected, namely, p-type or n-type so as to
produce a space charge layer at a surface portion of
80 the semiconductor.
    As the elastic surface wave amplifier disclosed
herein is so adapted that the surface wave signal
may be amplified through the parametric
amplification effect caused by supplying an a.c.
85 pumping power from a high-frequency power
source without causing a d.c. current to flow through
the semiconductor, it has such an excellent effect
that it can attain continuous wave without Joule heat
generation.
90 Further, as the disclosed device utilizes the surface
charge layer nonlinearity of the conductor obtained
by application of a d.c. bias voltage, layer nonlinear-
ity effect can be expected and accordingly the pump-
ing power necessary to obtain a given gain can be
95 reduced.
    Still further, as the device utilizes the parametric
amplifying effect by the surface charge layer non-
linearity, undesirable noise generation due to a
thermal noise derived from resistors etc. can be well
100 eliminated and amplification can be accomplished
with an excellent S/N ratio.

CLAIMS

105   1.   An elastic surface wave device, comprising:
a laminate composed of a semiconductor layer, a
piezo-electric material layer, and a protective film
layer interposed therebetween; a first electrode on a
surface of said piezo-electric material layer for appli-
110 cation of a d.c. bias voltage and supply of a pumping
power; and a second electrode on a surface of said
semiconductor layer for ohmic contact therewith.
    2.   An elastic surface wave device as set forth in
claim 1, wherein said piezoelectric material layer
115 has, input and output means for electrical signals
disposed spacedly on its surface and in the propagat-
ing path of elastic surface waves, and said first elec-
trode is coupled to means for supplying the pumping
power thereto.
120   3.   An elastic surface wave device as set forth in
claim 1, wherein said piezoelectric material layer has
at its one end a surface wave absorber disposed
thereon.
    4.   An elastic surface wave device as set forth in
125 claim 1, wherein said semiconductor layer is made of
silicon and said piezoelectric layer is made of zinc
oxide.
    5.   An elastic surface wave device, substantially
as herein before described with reference to Figure 1
130 or Figures 2 and 3 of the accompanying drawings.

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